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14. ABSTRACT

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LEGACY SYSTEM ENGINEERING

VPERC CONSORTIUM

Final Report/Utah

for work ending July 15, 2009

Submitted by
Prof. Rich Riesenfeld, Prof. Elaine Cohen, and Dr. David Johnson

University of Utah

September 4, 2009

1 VPERC and Legacy Systems Engineering

The VPERC consortium, including Hampton University, the University of Utah, and Arizone State University, have been working together to develop approaches for legacy systems engineering (LSE). Maintenance and further development of decades-old complex systems is a critical need for the continued effectiveness and efficiency of the US military, yet many of these systems no longer have suppliers or even detailed specifications available.

Prior work from VPERC addressed, in part, initial acquisition of CAD models from archival data, such as paper CAD drawings. Current efforts have been aimed at making these CAD models more amenable to re-engineering, through such strategies as higher-level information extraction and analysis from these parts, so that re-engineering efforts can be done more at a feature level than just working with plain geometry.

ASU's report detailed their research and results working with a Hampton University model embedded within a Utah assembly structure. They were able to automatically recognize common assembly features and extract functional capabilities. In this document, we will discuss some Utah efforts towards integrating analysis and design in a system that integrates functional analysis and geometric structure in a way to make rational re-engineering more approachable to a less-expert audience. More precisely, this reports highlights some results from each of these efforts in

- assembly creation
- assembly redesign
- assembly analysis

as shown in the following sections.

One interesting portion of the ASU results showed how an expensive FEA-analysis of a model was only slightly more accurate than a quick engineering calculation using some dimensional properties of the model. The Utah work expands this by showing how geometric models can be directly modified in functional terms by using fast engineering calculations and feedback mechanisms. Furthermore, current work is adapting faster, higher-accuracy spline element FEA from medical problems to mechanical models. At the end of this document, we show some possibilities and research questions associated with this approach.

2 Assembly Creation

The LSE problem often requires construction of new CAD models to support the redesign and/or analysis of existing parts. Working with Hampton and ASU, a sample drive shaft model was designed and detailed to test the group's efforts in analyzing the function of this part. In support of this, Utah designed a surrounding assembly so that ASU could test its assembly feature recognition technology (see Figure 1).

The larger research question for this portion of the work was developing tools to allow a designer to quickly and efficiently build up assemblies to support or improve parts from legacy systems. A key approach that made this possible is Utah's parametric-based CAD

design tools. By using key dimensional parameters from the drive shaft model, the surrounding assembly could be built to match the initial part. Given changes to the drive shaft, the corresponding dimensional changes automatically propagate through the larger assembly. Another key technology in the design is high-level design assistants, which, when given key parametric information, can create detailed, custom elements, such as the gear-train portion of the assembly. Such intent-driven modeling is one key to managing large legacy systems.

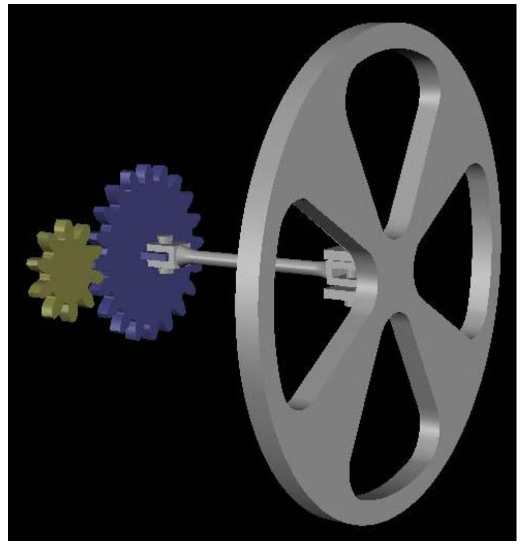

Figure 1: The test assembly built around that drive shaft. The connections between models were built using the shaft model's parametric information. The gear assembly was detailed using a high-level design assistant.

3 Functional Views of Geometric Models

For engineers involved in LSE, a crucial requirement is to design and re-engineer parts while monitoring functional requirements. In support of this, Utah has pursued research that tightly integrates the functional requirements and geometric instantiation of a model. This research has been published in the ASME-IDETC/DAC technical conference.

Designing a mechanical part is still largely a geometry-centric activity, even though both the design specification and model analysis is performed in terms of functional behaviors and physical properties. A critical job of a design engineer is to mentally track numerous functional constraints and partial analyses of a design while building up a geometric model.

One approach to dealing with this potential information overload has been to structure the geometric model, thereby automating model modification propagation or limiting the scope of possible changes. Another approach is to solve for geometric properties based on the functional specification, however, such optimization approaches are most suited for working on limited numbers of input parameters.

To address these difficulties, we have proposed interactive functional reparameterization of geometric parameters, or a *functional view* of a geometrically structured model. These functional views can provide immediate feedback, or, more importantly, can be directly linked to the underlying geometric parameters. This feedback-based linking allows a designer to modify geometric parameters by manipulating functional specifications, effectively reparameterizing the geometric structure into a functional one within a localized area.

3.1 An Illustrative Example

A simplified example may be useful in illustrating how dynamic reparameterization of the geometric structure can provide more intuitive functional views of the model.

Imagine a robotic assembly with a hollow tube arm defined by length, diameter, and inner diameter parameters, all geometric properties. However, the designer is instead interested in modifying the arm in terms of its potential loading. By placing a *fast*, cross-sectional analysis instrument that *estimates* safe maximum loading on the arm based on established design rules for cross-section modulus, and connecting those results back to the original inner diameter parameter through a feedback controller, the tube wall thickness can now change in response to changes in potential loadings, rather than through direct manipulation of the geometric parameter (see Figure 2). Thus, the geometric parameter for inner diameter can now temporarily be viewed and modified as a maximum load functional parameter. While the analysis tool is only an interactive approximation, it will give the designer enough rapid feedback to support a reasoned approach to shape modification in terms of functional properties, rather than just geometric ones. Later, as is currently done, more expensive, detailed analyses can be done at check-points in the design. Once an initial, satisfactory parameter is chosen, a computational alarm is set to notify the designer if safe maximum loading is exceeded during subsequent modifications.

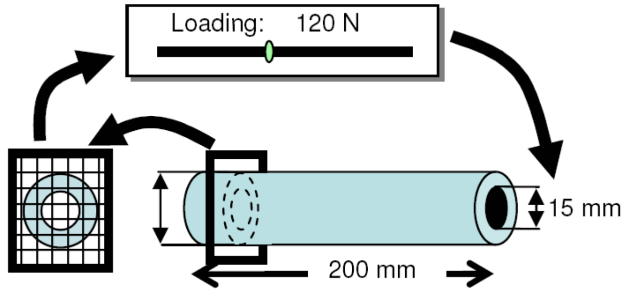

Figure 2: A functional design view using a cross-sectional maximum loading estimate and a feedback controller connected to a geometric wall-thickness parameter.

This example illustrates how analysis tools, in combination with appropriate feedback mechanisms, can transform the view of a structured geometric model from geometry parameters into another type, all while leaving the original geometric structure unperturbed. Essentially, new, temporary, functional structures can be imposed through feedback remapping of the underlying hierarchical geometric structure. This temporary restructuring can be thought of as a functional view of the model, as it does not permanently change the geometric structure of a design, it only allows changes to parameters in functional terms. Thus, one advantage of this approach is that it can be used to add functional modification handles to models developed elsewhere using purely geometric construction. Additionally, these feedback mechanisms can tie together previously unconnected parts of a design, encouraging more creative modifications and explorations of design possibilities beyond the rigid structure imposed by geometric specification. These feedback mechanisms can be attached or detached according to the interests of the designer, so they do not lead to a premature reduction in design possibilities through over-constraint.

3.2 System Development

This approach was implemented and tested in a system that used cross-sectional area and model volume to estimate loading strength and mass properties. These analysis tools were connected to geometric parameters through feedback mechanisms, allowing modification of model geometry based on functional requirements. The full paper has

additional details and results of tests on two different systems and is attached as Appendix A.

3.3 Discussion

This project demonstrates a new approach to human-augmented design tools. Rather than just permitting localized optimization of part function, a feedback mechanism transforms geometric parameters into temporary functional ones. This approach has been tested on two example design situations.

So far, just enough of the system has been implemented to demonstrate its basic function. We believe the real power of this approach will be demonstrated when there exists a rich set of analysis tools that can be quickly attached or detached to the design under consideration and that can interact with each other. Additional research issues are in the use of multiple-input-multiple-output (MIMO) feedback controllers and acceleration schemes for multiple and cascading simultaneous functional views. This approach matches well with current trends for multi-chip processing, as the analysis tools are highly distributable.

The advantage of this approach is that it ties together functional analysis and geometric modeling in a natural and useful way, opening the possibility of larger dissemination of analysis tools to those in the field doing maintenance and repair on complex legacy systems.

4 Spline Element FEA

There is a long-standing effort to integrate model representations for both design and analysis. However, current analysis tools still largely rely on a conversion process, which tends to make analysis more of a check-point tool rather than a part of the design process.

A further project from Utah is working on improving FEA for mechanical models. This reinforces the above efforts to develop tools for LSE assembly design and integrated design and analysis. Finite-element analysis is a vital tool for understanding the functional capabilities of a mechanical part. Most parts are broken into tetrahedral elements for FEA, which can be very generally applied. Faster and more accurate simulations can be run on models with hexahedral meshes; however, this regular structure is difficult to create for arbitrarily-shaped models.

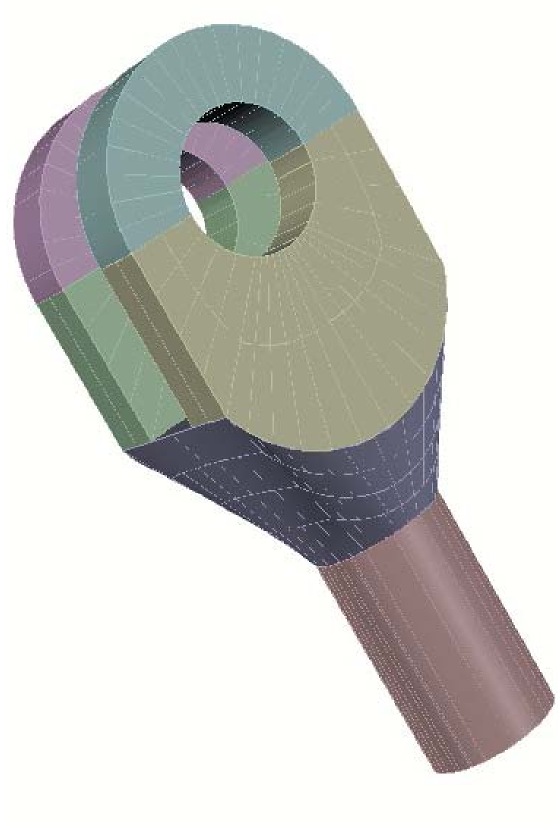

Figure 3: A modified spline model amenable to spline FEA analysis.

Recent efforts at a unified representation for design and analysis[1,2] have lead to the development of isogeometric analysis, where models are specified in a volumetric form and analyzed using higher-order elements. Utah has been working on extending this general theory of spline element FEA in the context of biological models, which also pose significant challenges in structuring them in away amenable to analysis.

For VPERC, we have made an initial model of the drive shaft part in a way that it can be used in spline FEA. The challenge is that while the original part is composed of numerous surfaces, with topological modifications such as holes added by trimming curves, the spline FEA analysis needs the model to be broken into regions defined as distorted cubes. Using our CAD modeling software, we have created a model meeting that criterion. There are exciting research opportunities to make this process more automated.

5 Future Work

We are excited to continue VPERC progress on the many issues facing LSE. In the end, LSE is a human-guided process, and we believe there are significant advances to be made in bringing more sophisticated, yet usable, tools to as broad a user base as possible, as significant improvements to LSE are most likely to be made by those responsible for the maintenance and engineering of our nation’s military legacy systems.

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[1] Hughes, T.J. and Cottrell, J.A. and Bazilevs, Y."Isogeometric analysis: CAD, finite elements, NURBS, exact geometry, and mesh refinement", in Computer Methods in Applied Mechanics and Engineering, vol. 194, pp. 4135-4195, 2005.

[2] J. A. Cottrell and T. T. Hughes and Y. Bazilevs, Isogeometric Analysis - Toward Integration of CAD and FEA, John Wiley and Sons, 2009

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Appendix A

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INTERACTIVE FUNCTIONAL REPARAMETERIZATION OF GEOMETRIC MODELS

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ABSTRACT
Engineering designs are often determined by functional considerations, yet modeled with purely geometric parameters. Because of this, a difficult part of a design engineer's job is tracking how changes to the geometric model might alter the functional performance of the design. This paper proposes a design interface that uses temporary functional views of geometric models to augment design engineers, helping them explore design space while continuously apprising them of the implications that modifications have on a design. The basic approach of the proposed interface is to use fast, interactive analysis tools in combination with feedback mechanisms to create temporary, functional design handles on top of the underlying geometric parametric structure. This design exploration tool is implemented in a research CAD system and demonstrated on illustrative examples.

INTRODUCTION
Designing a mechanical part is still largely a geometry-centric activity, even though both the design specification and model analysis is performed in terms of functional behaviors and physical properties. A critical job of a design engineer is to mentally track numerous functional constraints and partial analyses of a design while building up a geometric model.

One approach to dealing with this potential information overload has been to structure the geometric model, thereby automating model modification propagation or limiting the scope of possible changes. Another approach is to solve for geometric properties based on the functional specification, however, such optimization approaches are most suited for working on limited numbers of input parameters.

To address these difficulties, this paper proposes interactive functional reparameterization of geometric parameters, or a *functional view* of a geometrically structured model. These functional views can provide immediate feedback, or, more importantly, can be directly linked to the underlying geometric parameters. This feedback-based linking allows a designer to modify geometric parameters by manipulating functional specifications, effectively reparameterizing the geometric structure into a functional one within a localized area.

The primary contribution of this paper is the demonstration that optimization approaches can not only be used to meet some functional specification, but can also dynamically restructure a geometric parametric model to have functional modification

handles. The goal is to show that geometric specification and functional specification can coexist in a design system and a designer can think in terms of whichever is more useful at any particular moment. The overall motivation is aimed towards eventually creating a human-augmenting design system that encourages experimentation, creativity, and problem insight rather than the serial, highly-structured approach currently used.

The two main technical elements to accomplish this functional reparameterization are:

- Developing designer instantiated, lightweight analysis tools that can be used for rapid functional feedback on geometric changes.
- Applying feedback-based mechanisms that use these analysis tools to directly modify geometric parameters to meet desired functional properties.

In this paper, the focus is on the application of these elements to create functional views of a model, rather than any particular analysis tools and feedback mechanisms, although we believe that this research will create demand for more sophisticated tools. The combination of these elements will allow dynamic restructuring of geometric design parameters into functional parameters using feedback-based design views. Such restructuring will provide more natural and meaningful design modification handles to an engineer, leading to more experimentation and human-guided optimization of design.

An Illustrative Example

A simplified example may be useful in illustrating how dynamic reparameterization of the geometric structure can provide more intuitive functional views of the model. Imagine a robotic assembly with a hollow tube arm defined by length, diameter, and inner diameter parameters, all geometric properties. However, the designer is instead interested in modifying the arm in terms of its potential loading. By placing a *fast*, cross-sectional analysis instrument that *estimates* safe maximum loading on the arm based on established design rules for cross-section modulus, and connecting those results back to the original inner diameter parameter through a feedback controller, the tube wall thickness can now change in response

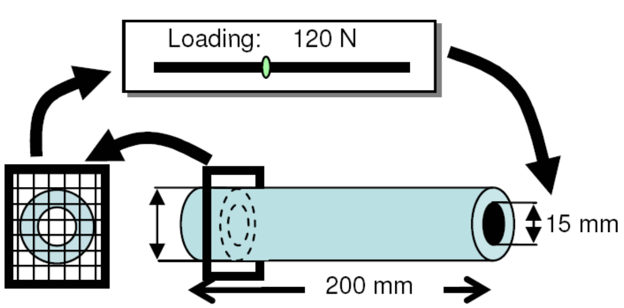

Figure 4: A functional design view using a cross-sectional maximum loading estimate and a feedback controller connected to a geometric wall-thickness parameter.

to changes in potential loadings, rather than through direct manipulation of the geometric parameter (see Figure 2). Thus, the geometric parameter for inner diameter can now temporarily be viewed and modified as a maximum load functional parameter. While the analysis tool is only an interactive approximation, it will give the designer enough rapid feedback to support a reasoned approach to shape modification in terms of functional properties, rather than just geometric ones. Later, as is currently done, more expensive, detailed analyses can be done at check-points in the design. Once an initial, satisfactory parameter is chosen, a computational alarm is set to notify the designer if safe maximum loading is exceeded during subsequent modifications.

This example illustrates how analysis tools, in combination with appropriate feedback mechanisms, can transform the view of a structured geometric model from geometry parameters into another type, all while leaving the original geometric structure unperturbed. Essentially, new, temporary, functional structures can be imposed through feedback remapping of the underlying hierarchical geometric structure. This temporary restructuring can be thought of as a functional view of the model, as it does not permanently change the geometric structure of a design, it only allows changes to parameters in functional terms. Thus, one advantage of this approach is that it can be used to add functional modification handles to models developed elsewhere using purely geometric construction. Additionally, these feedback mechanisms can tie together previously unconnected parts of a design, encouraging more creative modifications and explorations of design possibilities beyond the rigid structure imposed by geometric specification. These feedback mechanisms can be attached or detached according to the interests of the designer, so they do not lead to a premature reduction in design possibilities through over-constraint.

BACKGROUND

Products are designed in CAD systems and analyzed in CAE systems. Some CAD systems attempt algorithmically to propagate modifications of a shape model by what is termed *constraint based modeling* [1]. Many modeling systems today embody the related concepts of *parametric modeling* and feature based design [2]; that is, objects are defined in terms of meaningful higher level concepts, such as design features and manufacturing features, rather than raw geometry.

Engineering analysis is used to determine if a design satisfies specifications. The more faithful computational analysis codes are to behavioral constraints and geometry, the more difficult, time consuming, and complex the codes. There are many systems specific to various engineering disciplines, as well as more general purpose codes. Transforming the results of the analyses back into appropriate geometric modifications can also be difficult. Commercial packages, such as CATIA Analysis, have attempted to make analysis tools more approachable to a designer through user interfaces and faster response, and while invoking these tools is much more

convenient than even a few years ago, analysis still remains a time-consuming task.

Design Rule Analysis

In many iterations of the design process, the analysis is done manually. The designer typically uses lower order approximations to the physical characteristics and to the geometries. These simplifications are usually manually computed, so designer time and focus is lost to performing a variety of design checks and sizing computations throughout the design process using basic engineering design rules, paper, calculator, and computational packages such as MatLab. These computations are separate from the CAD system, but results from them are used to generate geometric design parameters for CAD systems. A commercial system, modeFRONTIER, is aimed at linking these small analyses into the CAD system by attaching to analysis inputs and outputs, but the primary use of this system to build an optimization layer on top of lightweight analysis tools. In contrast, the approach described here attempts to build designer intuition through functional restructuring of geometric parametric structures.

Finite-Element Analysis

Finite-element analysis (or FEA) remains the most accurate analysis method for engineering [3] and forms a key methodology for simulation, analysis, and validation. Research into new algorithms and codes have generally assumed the existence of an appropriate geometry model, while related research has focused on generating such models from CAD models [4]. It can be used on enormous problems as well as relatively simple ones. However, it requires careful preparation of the model, and typically can only be done in a batch-process manner. Thus, it is primarily used only at checkpoints in the design or for final validation and sometimes only on key elements of the design. Other approaches have sought to imbed FEA capabilities directly into the model, such as the approach taken by isogeometric analysis [5]. Careful precomputation and/or linearization of the model can also yield interactive results. Such an approach was taken in [6] to give a design engineer interactive haptic feedback on stress computations given model shape changes.

Integrated Shape Design and Optimization

The need to integrate shape design and engineering analysis is well recognized [7,8,9]. Multi-Disciplinary Optimization (MDO) [10,11] investigates creating a unified multidisciplinary optimization over multiple analyses in multiple disciplines. The complexity of MDO is such that a full optimization on a detailed design is rarely feasible. Structured approaches, such as collaborative optimization (CO), are needed to coordinate these complex analyses within a design group [12]. An alternate approach is to provide timely guidance to the design engineer to allow *design steering* [13], which has been demonstrated to promote greater design exploration over unguided methods [14]. Some commercial systems, such as SolidWorks, permit limited optimization of part parameters based on some functional metric.

Functional Design

Functional design is based on the premise that geometric parameters are rarely the primary handle into design changes and provides a set of objects that are able to be modified based on functional requirements rather than dimensional properties. It is applicable to assemblies for which the governing design rules can be turned into a collection of equations to generate geometry directly. An early example of this approach was done for propeller blade surfaces in [15]. Complex shapes for parts can be generated based on functional requirements, such as for camoid followers [16,17]. Kagen [18] embedded FEA with spline elements using a unified representation for both geometry and analysis, and demonstrated feasibility on an elastic linear rod and plate models. In many ways, the goals of functional design is similar to our goals; however, rather than creating a set of specific functional design objects, this project will allow a designer to easily create temporary functional-like objects on top of a geometric structure using lightweight analysis tools and interactive feedback-based modification.

Summary

The current state of the art is that design and analysis still largely occur in a non-integrated way. Furthermore, the more accurate and specific an analysis system is, the less likely it is to be integrated into the design process. Instead, we propose to allow analyses of interest to be attached to a design, and to have analysis results both inform the designer and locally modify relevant geometric parameters.

APPROACH

The approach taken in this paper is that interactive, approximate analysis tools that are integrated into the design process can help bridge the gap between functional goals and geometric specification. The specific mechanism to develop this approach is to allow a designer to interactively attach rapid analysis tools to regions of interest in a design, and to either use that functional analysis as feedback to the designer or to use the output of the analysis to directly modify geometric parameters of interest. We call this feedback modification a functional view of the model, as the geometry can now be changed using functional parameters of interest. The following sections describe which analysis tools currently are supported by the system, how the tools interact with the geometric model, and how a feedback tool can be used to change the geometric model parameters.

Interactive Analysis Tools

While we envision eventual development of a rich set of analysis tools, this research currently supports tools for cross-sectional area and for model mass properties. Since at least basic forms of these tools are commonly available in commercial CAD packages, they make good test cases for demonstrating the basic behavior of the approach and for

illustrating how feedback mechanisms can use existing analysis to create functional views.

Cross-Sectional Area Tool: The system's cross-sectional area tool is built upon a Boolean operation function for trimmed NURBS models. A flat cutting plane is intersected with the model at a region of interest chosen by the designer. Such human-guided placement has the advantage of drawing upon engineer knowledge and experience. The intersection curve is a discrete approximation to the true, smooth, intersection curve with the discretization based on a tolerance parameter. For a planar intersection curve, the area A circumscribed by a curve with n vertices (x_i, y_i) is found by

$$A = \frac{1}{2}\sum_{i=1}^{n}\left(x_i y_{i+1} - x_{i+1} y_i\right),$$

which can be seen as a trapezoidal decomposition of the area or as a discrete Green's Theorem. A generally-positioned intersection curve can be parameterized in the coordinate system of the cutting plane, so this formula can be directly applied. This cross-sectional area can then be used in various formulations and engineer's handbook types of computations to analyze functional properties of a part, yet the designer is not limited to the types of simple cross-sections commonly covered in these handbooks, opening up design possibilities.

Model Mass Properties Tool: The mass of a model in the system is computed by first finding the volume of the part. The volume is computed using surface integrals through application of Stokes' Theorem, These surface integrals are numerically integrated by breaking the surface into bilinear patches and then applying an exact quadrature rule for each patch. Each part in the system is tagged with a density value which allows computation of the part mass from the computed volume. Additional qualities such as centroid, moments of inertia, and principal axes are available within the same computation.

Integration of Analysis Tools

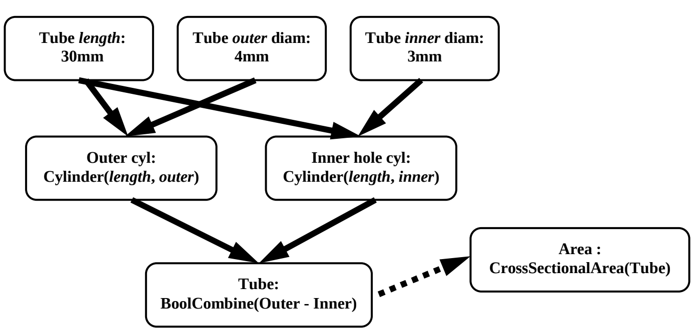

Figure 5: The geometric parameter graph for a simple tube model. The dimensional parameters at top propagate through solid primitive constructors, which are combined using Boolean operations into a tube.

This approach has been developed within the Alpha_1 research CAD environment. In this environment, models are built up parametrically, so that modifications to base primitives propagate through an acyclic dependency graph, refiring construction rules to create modified versions of the model geometry (Figure 5). Modeling is largely done through a scripting language, with commands similar to those inside the boxes of Figure 5. At any time in the modeling process, these lightweight analysis tools can be attached to regions of interest in the model. In Figure 5, a cross-sectional area tool is attached to the tube constructor in the graph. Therefore, changes to the model will cause updates to the analysis tools, keeping the designer apprised of any critical changes to functional properties.

Feedback-Based Reparameterization of Geometric Structure

The graph that structures a model uses geometric data as the base parameters. However, by using analysis and feedback tools interactively placed by the engineer, the analysis tools can locally restructure these geometric parameters into functional parameters of interest (see Figure 6). A proportional-integral-derivative (PID) controller has been implemented that connects a geometric parameter to the output of an analysis tool along with a desired value for that output. The PID controller manipulates the geometric parameter to create a desired output from the analysis. The engineer can now modify the controller setpoint, or target value, which acts as a local functional parameter to the model.

A PID controller was chosen to do this local reparameterization because of its generality. For simple models and simple graph structures many approaches from optimization and numerical methods would work well. However, as problem complexity increases, a more general approach is desirable, and PID controllers work well in such "black box" applications.

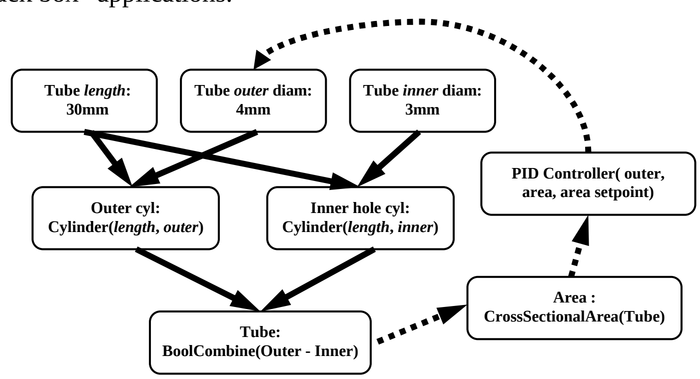

Figure 6: The dependency graph for a tube model. Dimensional parameters are up top, the final tube model is at the bottom, and the temporary connections made during functional reparameterization are shown at left with dotted arrows. The PID controller causes several iterations through the graph until the width parameter changes to reach a desired cross-sectional area of the tune. Currently, the graph is built using a scripting language.

RESULTS

The system was implemented and tested on some sample design problems. The feedback mechanism was able to

converge to a desired functional setpoint, and the designer could then use that setpoint parameter to adjust the geometry from a functional perspective.

A Cross-Sectional Area Example

In the first test, a simple tube was defined with a width, length, and inner offset geometric parameters. The cross-sectional area tool was attached to the tube. While in this case, the cross-sectional area is simple enough to find analytically, the cross-sectional area tool is general enough to use with more arbitrarily defined shapes.

Imagine the designer is interested in the maximum tensile strength of this part, which is directly related to the cross-sectional area. For simplicity, we will discuss this example in terms of cross-sectional area rather than any derived measure.

The initial setup is as seen in Figure 7 (top). The designer wants to determine the impact of different load requirements on the tube geometry. By connecting the tube width parameter to the PID controller and giving a desired cross-sectional area, the system converges to the state in the middle figure. If the designer then decides instead to investigate the wall thicknesses impact, the feedback generates the bottom figure.

However, used in this way, the tool is merely providing local optimization. Instead, the designer may manipulate the functional value directly and observe the changes to the model geometry. In our system, this is done within a scripting interface by giving the functional setpoint a new value. In a more developed interface, the setpoint could be changed by slider control, allowing interactive exploration of the new functional parameter. This use promotes exploration and understanding of the parametric family, and intuition into the tradeoffs between different functional requirements.

Run on a 2.1 GHz Pentium 4 PC, the system can compute new geometric parameters given changes to the functional value in 1.5 seconds. When manipulating the functional value, the response rate is increased because of increased temporal coherence – the state does not have to change very much to meet the new functional value. This interactive feedback provides a local functional reparameterization of the geometric structure.

A Neutral Axis Deflection Example

A more complex example is derived from a model used in the undergraduate Formula SAE competition. The car shell is modeled with varying thickness. The area where the driver will sit is open at top, and is formed with a cutout on the original solid shell model. This cutout moves a sectional center of mass closer to the bottom of the model, since there is no mass on top to counterbalance the bottom. This centroid, or neutral axis, position decreases the stiffness of the vehicle, as the moment arm from the centroid to the top of the car is not minimized.

The model is parameterized with a vertical offset parameter for each of the cross-sectional curves that define the inner and outer surfaces of the shell. The designer can explore the effect of shifting material from the bottom of the vehicle to the top with this offset parameter, which has the effect of shifting the centroid. In addition, this offset parameter can be used in a feedback loop to give the designer direct control over the permissible amount of deflection. By setting different deflection values in the feedback controller setpoint, the offset parameter is changed to meet the new requirements,

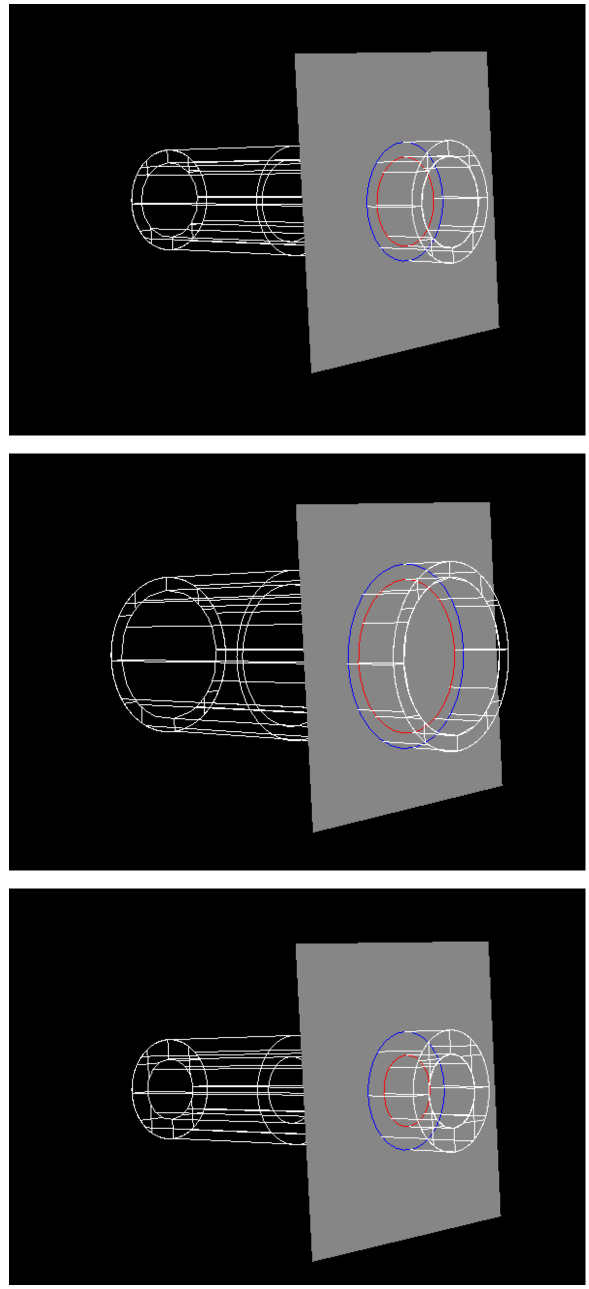

Figure 7: The feedback controller can modify geometric parameters of interest. (top) The original tube shown with the shaded cutting plane and the cross-sectional curves in blue and red. (middle) The PID controller manipulates the tube width parameter. (bottom) The manipulated parameter is inner wall diameter.

The racecar body is shown in Figure 8 (top). The cutout for the driver shifts the neutral axis in that region, causing an

undesirable amount of deflection in the body. The designer could experiment with an inner surface offset parameter and evaluate the changes to the model and the functional implications. Instead, the feedback controller was used to relate the offset parameter to the vertical location of the centroid.

Figure 8 (middle, bottom) shows the initial location of the centroid and the final location, respectively. Note how the structural mass of the cross-section has shifted from the bottom of the car, where it is not needed, to the top. The amount of offset is exaggerated to make the changes more visible.

Based on this functional exploration, the designer may decide that too much material needs to be removed from the bottom of the car to adequately move the neutral axis. In a more sophisticated version of this paper's approach, other lightweight analysis tools could be monitoring structural strength while the neutral axis location is being modified. Instead, the designer may choose some other mechanism, such as wider flanges at top to shift the centroid. This is an example of how natural control over functional parameters may drive larger, more creative changes to a design.

In this example, the speed of the feedback is limited by the precise Boolean operations used to compute the slice and the centroid limit. Initial convergence of the feedback loop took 8 seconds. As before, interactive manipulation of the functional parameter was faster than single queries due to coherence.

DISCUSSION AND CONCLUSION

This paper demonstrates a new approach to human-augmented design tools. Rather than just permitting localized optimization of part function, a feedback mechanism transforms geometric parameters into temporary functional ones. This approach has been tested on two example design situations.

So far, just enough of the system has been implemented to demonstrate its basic function. We believe the real power of this approach will be demonstrated when there exists a rich set of analysis tools that can be quickly attached or detached to the design under consideration and that can interact with each other. Additional research issues are in the use of multiple-input-multiple-output (MIMO) feedback controllers and acceleration schemes for multiple and cascading simultaneous functional views. This approach matches well with current trends for multi-chip processing, as the analysis tools are highly distributable.

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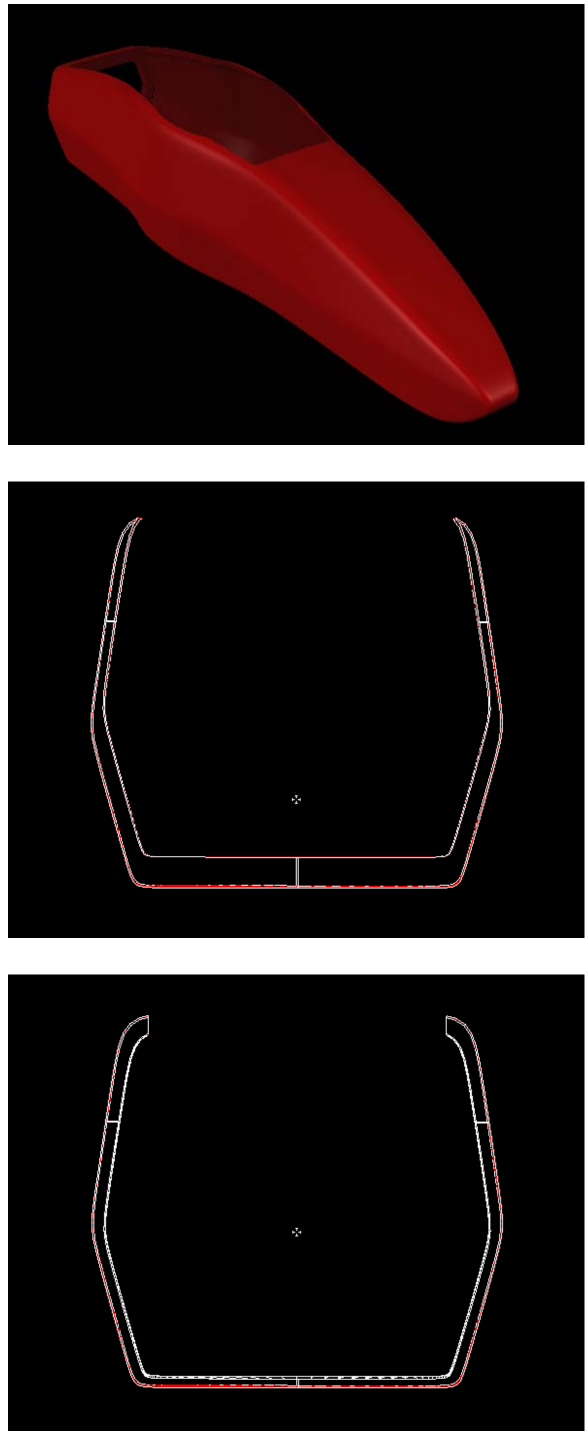

Figure 8: Analysis of deflection of a racecar body. (top) The racecar model. (middle) A cross-sectional slice with the mass centroid shown with a small crosshair. (bottom) By controlling an offset parameter for the inner surface, mass is moved to the top, raising the centroid.

those of the authors and do not necessarily reflect the views of the sponsoring agencies.

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